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# The properties of a large volume-limited sample of face-on low surface brightness disk galaxies *

Guo-Hu Zhong[1,2,3,4], Yan-Chun Liang[1,2], Feng-Shan Liu[5], Francois Hammer[4], Karen Disseau[4,6] and Li-Cai Deng[1,2]

[1] National Astronomical Observatories, Chinese Academy of Sciences, Beijing 100012, China; *ghzhong@nao.cas.cn*
[2] Key Laboratory of Optical Astronomy, National Astronomical Observatories, Chinese Academy of Sciences, Beijing 100012, China
[3] Graduate University of Chinese Academy of Sciences, Beijing 100049, China
[4] GEPI, Observatoire de Paris-Meudon, 92195 Meudon, France
[5] College of Physical Science and Technology, Shenyang Normal University, Shenyang 110034, China
[6] Univ Paris Diderot, Sorbonne Paris Cité, GEPI, UMR8111 CNRS, Observatoire de Paris, F-92190 Meudon, France

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**Abstract** We select a large volume-limited sample of low surface brightness galaxies (LSBGs, 2021) to investigate in detail their statistical properties and their differences from high surface brightness galaxies (HSBGs, 3639). The distributions of stellar masses of LSBGs and HSBGs are nearly the same and they have the same median values. Thus this volume-limited sample has good completeness and is further removed from the effect of stellar masses on their other properties when we compare LSBGs to HSBGs. We found that LSBGs tend to have lower stellar metallicities and lower effective dust attenuations, indicating that they have lower dust than HSBGs. The LSBGs have relatively higher stellar mass-to-light ratios, higher gas fractions, lower star forming rates (SFRs), and lower specific SFRs than HSBGs. Moreover, with the decreasing surface brightness, gas fraction increases, but the SFRs and specific SFRs decrease rapidly for the sample galaxies. This could mean that the star formation histories between LSBGs and HSBGs are different, and HSBGs may have stronger star forming activities than LSBGs.

**Key words:** galaxies: fundamental parameters — galaxies: general — galaxies: statistics — galaxies: stellar content

## 1 INTRODUCTION

Galaxies with surface brightness fainter than $\mu_0(B) = 21.65 \pm 0.3$ mag arcsec$^{-2}$ are well known as low surface brightness galaxies (LSBGs, Freeman 1970). Yet, owing to their faintness compared with the night sky, they are hard to find. Hence their contribution to the local galaxy population has been

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underestimated for a long time. However it is found that LSBGs could represent a significant fraction of galaxy number density in the universe (O'Neil et al. 2000; Minchin et al. 2004; Trachternach et al. 2006) and may comprise up to half of the local galaxy population (McGaugh et al. 1995).

During the last four decades, LSBGs have been widely studied both in observations (Impey et al. 1996; O'Neil et al. 1997; Trachternach et al. 2006; Haberzettl et al. 2007a; Pizzella et al. 2008; Ulmer et al. 2011; Morelli et al. 2012) and theoretical work (Dalcanton et al. 1997; Alard 2011). In particular, thanks to modern digital sky surveys, a wealth of observational data with high quality has undoubtedly become important in allowing us to study the photometric and/or spectroscopic properties of LSBGs with large samples, even in multi-wavelengths. For example, (1) the statistical properties (Zhong et al. 2008, 2010), the metallicities (Liang et al. 2010), the environment (Rosenbaum & Bomans 2004; Rosenbaum et al. 2009; Galaz et al. 2011), and the stellar red holes (Bergvall et al. 2010) of LSBGs from the Sloan Digital Sky Survey (SDSS); (2) the stellar populations (Zhong et al. 2008) and HI observations (Monnier Ragaigne et al. 2003a,b) of LSBGs from the Two Micron All Sky Survey (2MASS); (3) star formation efficiency (Boissier et al. 2008) from Galaxy Evolution Explorer (GALEX); (4) infrared properties (Hinz et al. 2007) from the Spitzer Space Telescope. In addition, the multi-wavelength spectral energy distributions have also been investigated (Gao et al. 2010).

From the studies above, LSBGs are generally found to have lower metallicities (McGaugh 1994; Galaz et al. 2006; Haberzettl et al. 2007b; Liang et al. 2010), lower surface densities that could explain their slow evolution (Mo et al. 1994; Gerritsen & de Blok 1999; van den Hoek et al. 2000), lower fractions of active galactic nuclei (Impey et al. 2001; Mei et al. 2009; Liang et al. 2010; Galaz et al. 2011), lower star formation rates (SFRs, van den Hoek et al. 2000), higher $M_*/L$ ratios (Sprayberry et al. 1995), higher gas fractions, and they are located in lower density regions (Mo et al. 1994; Rosenbaum & Bomans 2004; Rosenbaum et al. 2009; Galaz et al. 2011) than what is typically found in high surface brightness galaxies (HSBGs).

Despite these impressive progresses, there are still several challenges in the study of LSBGs, such as many aspects of their formation and evolution. Moreover, the studies of $M_*/L$, SFR or gas content of LSBGs are based on very small samples, less than two hundred LSBGs (e.g. McGaugh & de Blok 1997; Burkholder et al. 2001). In particular, a magnitude-limited survey will be affected by selection effects, which result from the inability of the survey to detect fainter galaxies at larger redshifts (e.g. Impey et al. 1996; Zhong et al. 2008). One way to avoid these effects is through using a volume-limited sample, in which a maximum redshift and a minimum absolute magnitude are chosen so that a complete sample is obtained in this redshift and magnitude range. Some properties could be different between the volume-limited sample and the magnitude-limited sample. For example, in Zhong et al. (2008), the relation between disk scale-length and $\mu_0(B)$ are different between the total sample and the volume-limited sample. This difference is caused by selection of the volume-limited sample from the magnitude-limited sample. When selecting volume-limited LSBGs at $z < 0.1$, we exclude two parts: on the one hand, LSBGs with relatively lower redshift (smaller distance) and lower luminosity (see bottom-left of Fig. 1) are excluded, which should lead to smaller disk scale-length (see figs. 4 and 5 of Zhong et al. 2008) as well as fainter surface brightness (see fig. 3 of Zhong et al. 2008); on the other hand, LSBGs with relatively higher redshift (larger distance) and higher luminosity (see top-right of Fig. 1) are excluded, which should lead to larger disk scale-length (see figs. 4 and 5 of Zhong et al. 2008) as well as brighter surface brightness (see fig. 3 of Zhong et al. 2008). Excluding LSBGs with smaller disk scale-length at the fainter surface brightness end and larger disk scale-length at the brighter surface brightness end from figure 7 of Zhong et al. (2008) results in the relation between disk scale-length and surface brightness of their figure 13(g), the more obvious correlation between log$h$ and $\mu_0(B)$. Furthermore, in Galaz et al. (2011), they point out the strong dependence of the absolute magnitude versus redshift in the SDSS spectroscopic catalog (a magnitude-limited catalog), and the trend of absolute magnitude on the galaxy's size (see fig. 1 of Galaz et al. 2011 for more details).

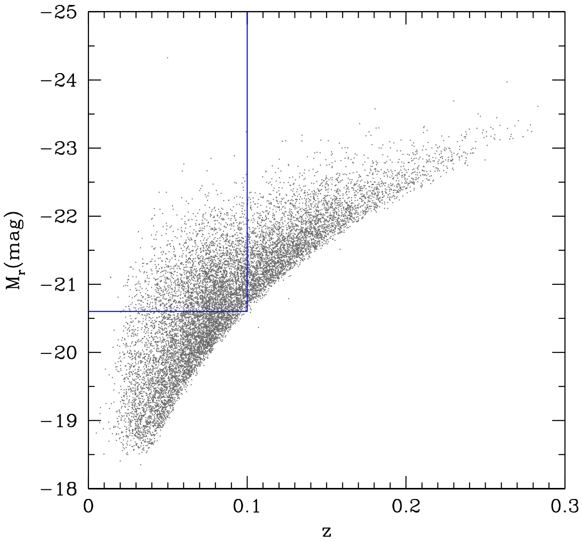

**Fig. 1** The relationship between $r$ band absolute magnitude and redshift for LSBGs. The vertical line refers to $z = 0.1$ and the horizontal line is the corresponding $M_r$. The top-left region marked by solid lines is selected as the volume-limited sample.

In this work, with the advent of the large sky survey of SDSS, it is now possible to dramatically extend the sample size in studies of SFRs, $M_*/L$, and gas content of LSBGs. Moreover, this large amount of high quality data will undoubtedly be important to allow us to study the properties of those galaxies more carefully. Furthermore, in order to avoid the bias of magnitude-limited samples, we apply constraints to a large volume-limited sample of LSBGs (more than two thousand) to study their statistical properties in detail, and then compare them with HSBGs. The volume-limited samples could be a fair comparison between LSBGs and HSBGs, and they improve the completeness of the samples.

This is one in our series of works (Zhong et al. 2008, 2010; Liang et al. 2010; Gao et al. 2010; Chen et al. in preparation) to study the properties of a large sample of LSBGs and compare their differences with HSBGs. This paper is organized as follows. We describe our sample selection in Section 2 and present the results in Section 3. In Section 4 we discuss our results. In Section 5 we summarize this work. Throughout the paper, a cosmological model with $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_M = 0.3$ and $\Omega_\lambda = 0.7$ is adopted.

## 2 SAMPLES

The data analyzed in this study were drawn from the SDSS, which is an imaging and spectroscopic survey that will obtain photometry of one-quarter of the sky and spectra of nearly one million objects. The imaging data were collected in the $u,\ g,\ r,\ i,\ z$ bands mounted on the SDSS 2.5 m telescope at Apache Point Observatory. The spectra are flux- and wavelength-calibrated, with 4096 pixels from 3800 to 9200 Å at $R \sim 1800$. The details of the survey strategy and overview of the data pipelines and products can be found in York et al. (2000) and Stoughton et al. (2002). In this paper, for the sample galaxies, the stellar masses, mass-to-light ratios, and effective dust attenuations are from

Kauffmann et al. (2003); the SFRs and specific SFRs are from Brinchmann et al. (2004); the stellar metallicities are from Gallazzi et al. (2005). All of those data can be found in the MPA/JHU website[1].

Same as Zhong et al. (2008), the sample is selected from the main galaxy sample (MGS, Strauss et al. 2002) of the SDSS Data Release Four[2] (DR4, Adelman-McCarthy et al. 2006). We prefer to use DR4 because some of the parameters we use here have just been updated using DR4 by the MPA/JHU groups, e.g. stellar metallicities from Gallazzi et al. (2005). The detailed criteria of sample selection can be found in Zhong et al. (2008). We describe it briefly as follows.

1. *fracDev*$_r < 0.25$. The parameter *fracDev*$_r$ indicates the fraction of luminosity contributed by the de Vaucouleurs profile relative to that from the exponential profile in the $r$-band. This is to select disk dominated galaxies which can minimize the effect of bulge light on disk galaxies.
2. $b/a > 0.75$ (corresponding to the inclination $i < 41.41°$). This is to select nearly face-on galaxies, which can minimize the extinction. $a$ and $b$ are the semi-major and semi-minor axes of the fitted exponential disk respectively.
3. $M_B < -18$. This is to exclude a few dwarf galaxies contained in the sample.
4. We select objects with $\mu_0(B) \geq 22.0$ mag arcsec$^{-2}$ as LSBGs and $\mu_0(B) < 22.0$ mag arcsec$^{-2}$ as HSBGs. The $\mu_0(B)$ values are calculated following the method of Zhong et al. (2008, their eq. 6). After this step, we get 12 282 LSBGs and 18 051 HSBGs.
5. In order to avoid the bias introduced from the differences in both the redshift and absolute magnitude distributions for the samples, we extract volume-limited samples from the $M_r - z$ plane by considering $z < 0.1$ and galaxies brighter than the corresponding $M_r$. After this step, we get 3313 LSBGs and 4722 HSBGs.

   The relationship between $r$ band absolute magnitude and redshift for LSBGs is shown in Figure 1. The vertical line refers to $z = 0.1$, while the horizontal line is the corresponding $M_r$. The galaxies located in the top-left region within the solid lines are selected as our volume-limited sample.
6. In this work, in order to obtain good values of the parameters, we just select galaxies with all measurements of stellar masses, mass-to-light ratios, effective dust attenuations, SFRs, specific SFRs, and stellar metallicities. Finally, we obtain the volume-limited samples of 2021 LSBGs and 3639 HSBGs following the volume-limited sample selections of Zhong et al. (2008).

All the magnitudes that we quote above are $K$-corrected and corrected for Galactic reddening (Blanton et al. 2005).

## 3 RESULTS

Using large volume-limited samples of LSBGs and HSBGs, we present the properties of LSBGs (e.g. stellar metallicities, effective dust attenuations, mass-to-light ratios, and SFRs) and compare them with HSBGs. The stellar metallicities are from Gallazzi et al. (2005), in which they determine the stellar metallicities by a spectroscopic method that used a few line strength indices to measure the stellar population properties of galaxies. The stellar masses, mass-to-light ratios, and effective dust attenuations in the $z$ band are from Kauffmann et al. (2003), all of which are generated by using a large library of Monte Carlo calculations of different star formation histories, including starbursts of varying strength and a range of metallicities. The SFRs are from Brinchmann et al. (2004), who built a picture of the nature of star-forming galaxies at $z < 0.2$ by comparing physical information extracted from the emission lines (e.g. H$\alpha$) with continuum properties, and developed a method for aperture correction using resolved imaging. This method essentially removes all aperture bias in their estimate of SFRs, allowing an accurate estimate of the total SFRs in galaxies. One may wish to

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[1] *http://www.mpa-garching.mpg.de/SDSS/DR4*

[2] *http://www.sdss.org/DR4*

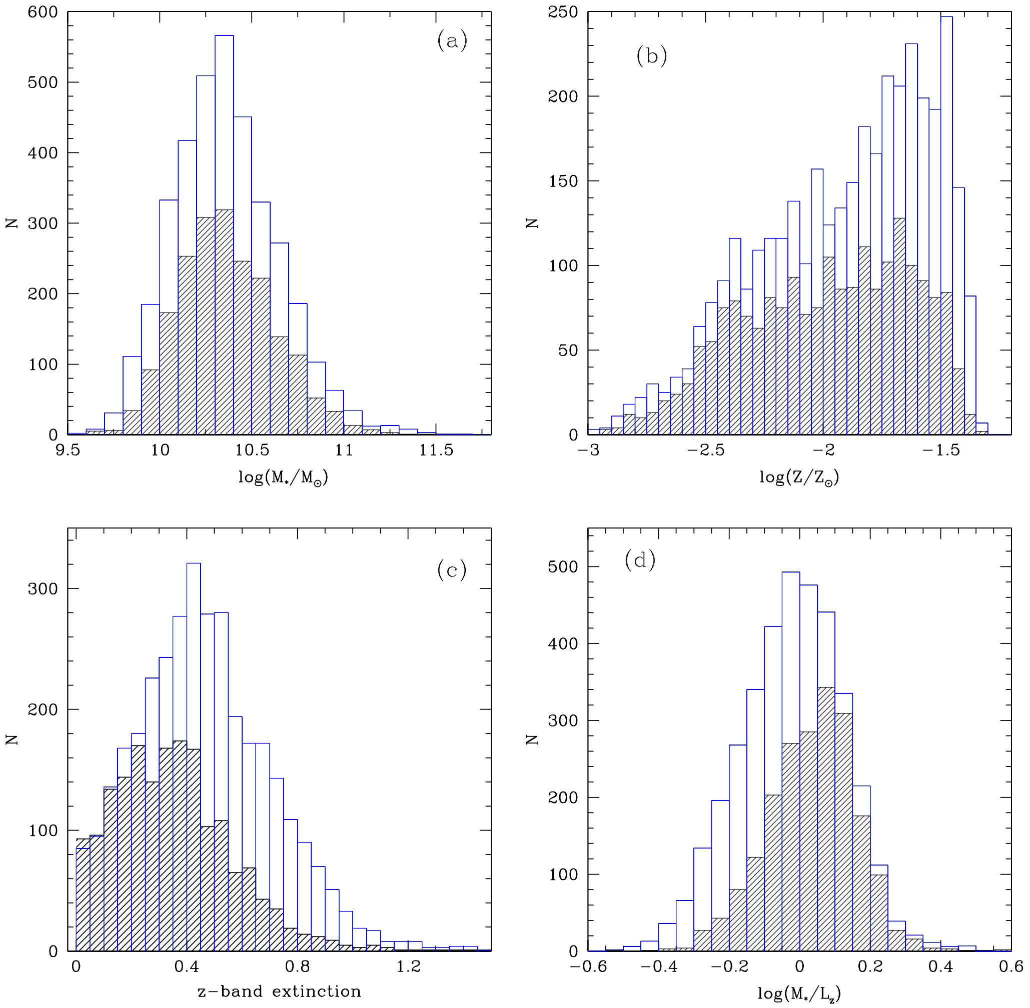

**Fig. 2** Histogram distributions of some parameters for LSBGs (shadowed regions) and HSBGs (unfilled regions): (a) the distributions of stellar masses ($\log(M_*/M_\odot)$), (b) the stellar metallicities ($\log(Z/Z_\odot)$), (c) the effective dust attenuations in the $z$ band, and (d) the histogram distributions of dust-corrected mass-to-light ratios in the $z$ band.

refer to the papers of Gallazzi et al. (2005), Kauffmann et al. (2003), and Brinchmann et al. (2004) regarding the properties of galaxies in SDSS.

### 3.1 Distributions of Stellar Masses, Stellar Metallicities, Effective Dust Attenuations and Stellar Mass-to-light Ratios

Figure 2 shows the histogram distributions of some parameters for LSBGs and HSBGs. They are the distributions of the stellar masses (Fig. 2(a)), the stellar metallicities (Fig. 2(b)), effective dust attenuations in the $z$ band (Fig. 2(c)), and dust-corrected mass-to-light ratios in the $z$ band (Fig. 2(d)). The shadowed regions are for LSBGs, while the unfilled regions are for HSBGs.

From the distributions of stellar masses in Figure 2(a), we can see that LSBGs and HSBGs span nearly the same range and have very similar distributions. Kolmogorov-Smirnov tests show that the difference in the means of distributions for LSBGs and HSBGs is only 6.6%. The median values of stellar masses of volume-limited samples of LSBGs and HSBGs are both $2.19\times10^{10}\,M_\odot$. This result in our volume-limited samples is different from Liang et al. (2010) who showed that galaxies with lower surface brightness generally have smaller stellar masses. This difference may be because they use magnitude-limited samples that could be affected by the completeness, while we use volume-limited samples to avoid such selection effects. Moreover, the very similar distributions of stellar mass between LSBGs and HSBGs can help obtain a fairer comparison in the following sections since the effect of stellar masses is nearly removed.

The stellar metallicities [log($Z/Z_\odot$)] of LSBGs also span nearly the same range as that of HSBGs (Fig. 2(b)), however, the median value of stellar metallicities for LSBGs is –1.95 which is 0.11 dex (1.3 times) lower than that of HSBGs (–1.84). Kolmogorov-Smirnov tests show that the difference in the means of distributions for LSBGs and HSBGs is 16.0%. The result that LSBGs have lower stellar metallicities is consistent with the lower metallicities of LSBGs found in the gas-phase (McGaugh 1994, Galaz et al. 2006, Haberzettl et al. 2007b, Liang et al. 2010). Liang et al. (2010) found that the decreasing of metallicity with decreasing surface brightness could be due to the decreasing stellar mass with decreasing surface brightness. In our volume-limited samples, however, LSBGs have similar stellar mass distributions as HSBGs, yet they still have lower metallicities. Thus, lower stellar masses are not enough to explain the lower metallicities of LSBGs. The LSBGs could have different star formation histories compared to HSBGs.

Figure 2(c) shows that the LSBGs have lower effective dust attenuations in the $z$ band. The median value is 0.34 mag, which is 0.11 mag smaller than that of HSBGs whose median value of effective dust attenuation in the $z$ band is 0.45. Kolmogorov-Smirnov tests show that the difference in the means of distributions for LSBGs and HSBGs is up to 26.4%. The lower effective dust attenuations in the red band (the $z$ band) is consistent with the results in the $V$ band (e.g. Liang et al. 2010), which means that LSBGs could contain less dust than HSBGs (McGaugh 1994; Hinz et al. 2007).

In Figure 2(d), we show the distributions of dust-corrected $z$ band mass-to-light ratios; shadowed and unfilled regions are for LSBGs and HSBGs respectively. The LSBGs tend to have higher mass-to-light ratios than HSBGs. Kolmogorov-Smirnov tests show that the difference in mean of distributions between LSBGs and HSBGs is 23.7%. The median value of stellar mass to $z$ band luminosity ratios ($M_*/L_z$) is 1.11, that is 0.15 (1.4 times) higher than that of HSBGs with median $M_*/L_z$ of 0.96. The high $M_*/L_z$ ratios either point toward galaxies early in their evolution that have not converted gas into stars or reflect more recent accumulation of gas by an evolved stellar population (Burkholder et al. 2001). This result may also indicate different star formation histories between LSBGs and HSBGs.

## 3.2 Gas Contents

Gas fraction can be used to quantify galaxy evolution (e.g. McGaugh & de Blok 1997; Burkholder et al. 2001). Assuming a constant $M_*/L$, it is believed that LSBGs are considered to be gas-rich galaxies, which may result from the fact that LSBGs have not effectively converted gas into stars. In our work, we first calculate the HI gas-to-stellar mass ratio (log[$G/S$]) by using the formula of Zhang et al. (2009, see their eq. (4) for more details)

$$\log(G/S) = -1.73238(g-r) + 0.215182\mu_i - 4.08451\,, \tag{1}$$

where $G$ and $S$ refer to HI mass ($M_{\rm HI}$) and stellar mass ($M_*$) respectively, and $g$ and $r$ are the apparent magnitudes from SDSS in the $g$ and $r$ bands respectively, both of which are $K$-corrected and corrected for Galactic reddening (Blanton et al. 2005). The $\mu_i$ is surface brightness in the SDSS

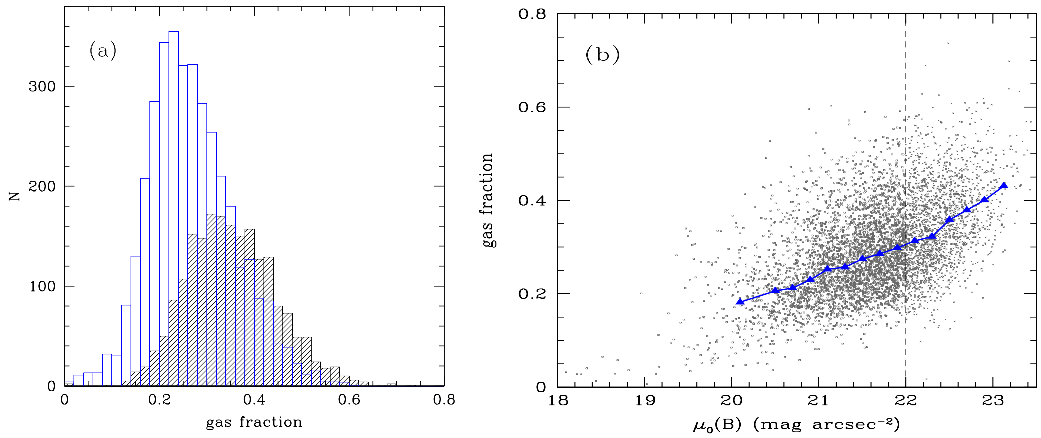

**Fig. 3** The histogram distributions of gas fraction (a). Shadowed and unfilled regions are for LSBGs and HSBGs respectively. The relation between gas fraction and surface brightness (b). The solid triangles and line denote the median values with surface brightness bins. The vertical dashed line marks the boundary of LSBGs and HSBGs.

$i$ band, which is defined as $\mu_i = m_i + 2.5\log(2\pi R_{50}^2)$, where $m_i$ is the apparent magnitude in the $i$-band that is also $K$-corrected and corrected for Galactic reddening (Blanton et al. 2005), and $R_{50}$ is the radius (in units of arcsec) enclosing 50 percent of the total Petrosian $i$-band flux. Then the HI mass can be calculated from log($G/S$) because the stellar mass is available (Kauffmann et al. 2003). Finally, one can get the gas fraction from $f_{\rm g} = M_{\rm g}/(M_{\rm g} + M_*)$, where $M_{\rm g} = 1.4M_{\rm HI}$ (e.g. McGaugh & de Blok 1997; Schombert et al. 2001).

We show the histogram of the calculated gas fraction in Figure 3(a), from which we can see that the gas fraction of LSBGs spans nearly the same range as that of HSBGs but is more likely to be distributed in the region with a higher gas fraction. We try our best to find related work on gas fraction of LSBGs to compare with our results, and found three related cases (i.e. McGaugh & de Blok 1997; Schombert et al. 2001; Burkholder et al. 2001). The range of gas fraction of our volume-limited LSBGs is approximately from 15% to 70%, which is very similar to the results in McGaugh & de Blok (1997) for a small sample of LSBGs (17% to 77%). Schombert et al. (2001) found that a majority of the galaxies in their disk samples having a gas fraction below 50% peaked at 30%, whereas in the LSB dwarf galaxies over 90% of the galaxies have a gas fraction greater than 30%. For our volume-limited LSBGs, most have gas fraction below 70% with a median value of 34.6%. This result is higher than that of the disk sample of Schombert et al. (2001), but lower than that of their LSB dwarf galaxies. The reason is that our volume-limited LSBGs contain more brighter galaxies without any dwarf galaxies (Zhong et al. 2008). The median value of gas fraction of our LSBGs is quite similar to that of McGaugh & de Blok (1997) with a small sample of LSBGs (median value of 40.1%), only 5.5% higher than ours (34.6%). Moreover, the median value of gas fraction for the our LSBGs is 8.7% higher than that of HSBGs (median value of 25.9%), thus, LSBGs are indeed gas-rich galaxies. Kolmogorov-Smirnov tests show that the difference in the means of distributions for LSBGs and HSBGs is bigger, up to 48.7%.

Furthermore, there is a tight correlation between gas fraction and surface brightness (the Spearman rank order correlation coefficient is 0.51) demonstrating that galaxies with lower surface brightness have higher gas fraction (Fig. 3(b)). This relation has been found in some previous studies

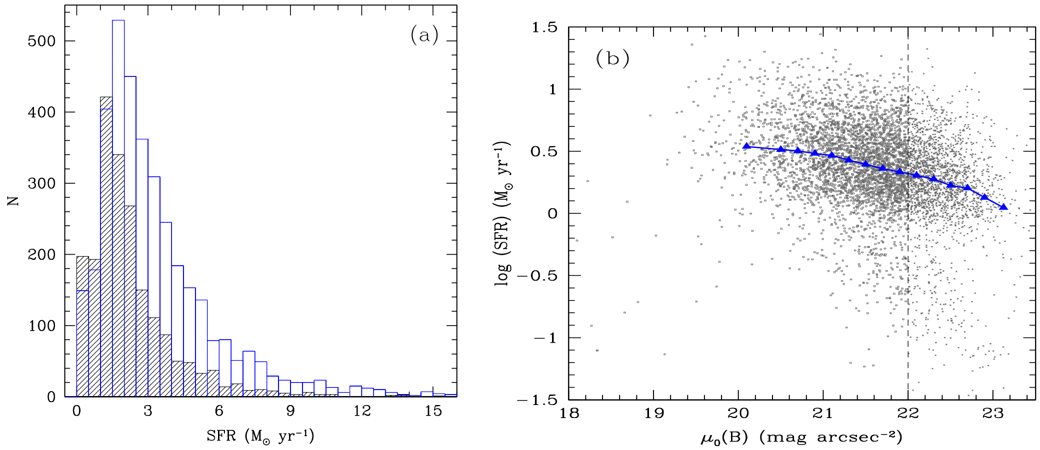

**Fig. 4** The histogram distributions of SFRs (a). Shadowed and unfilled regions are for LSBGs and HSBGs respectively. The relation between SFRs and surface brightness (b). Solid triangles, the solid line, and the dashed line are the same as in Fig. 3.

with very small samples. For example, McGaugh & de Blok (1997) found the correlation coefficient between gas fraction and surface brightness is 0.63, which is slightly tighter than ours. Schombert et al. (2001), who used chemical and spectrophotometric models from Boissier & Prantzos (2000), also predict the general trend of higher gas fraction with fainter surface brightness.

Though the correlation we find shows more scatter than those found by McGaugh & de Blok (1997), Schombert et al. (2001), and Burkholder et al. (2001), our conclusion is similar to theirs: LSBGs tend to be gas-rich. The high gas fraction of LSBGs could indicate that either these galaxies have experienced delays in formation and are just beginning to form stars or their ongoing star formation is inefficient and/or sporadic (Burkholder et al. 2001).

Moreover, the slope of gas fraction versus surface brightness for LSBGs is slightly steeper than that of HSBGs.

### 3.3 Star Formation Rates

It is shown that the typical gas surface densities for LSBGs are below the Kennicutt criterion for ongoing star formation (Kennicutt 1989; van der Hulst et al. 1993) which results in a suppressed current SFR (Boissier et al. 2008; Schombert et al. 2011). Thus the SFRs of LSBGs should be lower than those of HSBGs. In Figure 4(a), we show the histogram distributions of SFRs for both LSBGs (shadowed regions) and HSBGs (unfilled regions). We can see that LSBGs are more likely to have lower SFRs. Kolmogorov-Smirnov tests show that the difference in the means of distributions for LSBGs and HSBGs is 30.7%. The median value of SFRs for LSBGs is 1.77 $M_\odot$ yr$^{-1}$ which is 0.86 $M_\odot$ yr$^{-1}$ smaller than that of HSBGs that have median SFRs of 2.63 $M_\odot$ yr$^{-1}$. Moreover, the SFRs drop quickly with decreasing surface brightness (see Fig. 4(b)). The Spearman rank order correlation coefficient is –0.32, which could suggest that higher surface brightness galaxies are undergoing stronger star forming activities than the lower ones.

However the SFRs of LSBGs span a wide range, and the SFRs of LSBGs are not as low as the results in the previous studies (e.g. 0.02–0.8 $M_\odot$ yr$^{-1}$, van den Hoek et al. 2000). The reason for the relatively higher SFRs for LSBGs may be that we use a volume-limited sample of LSBGs, which selects the brighter ones.

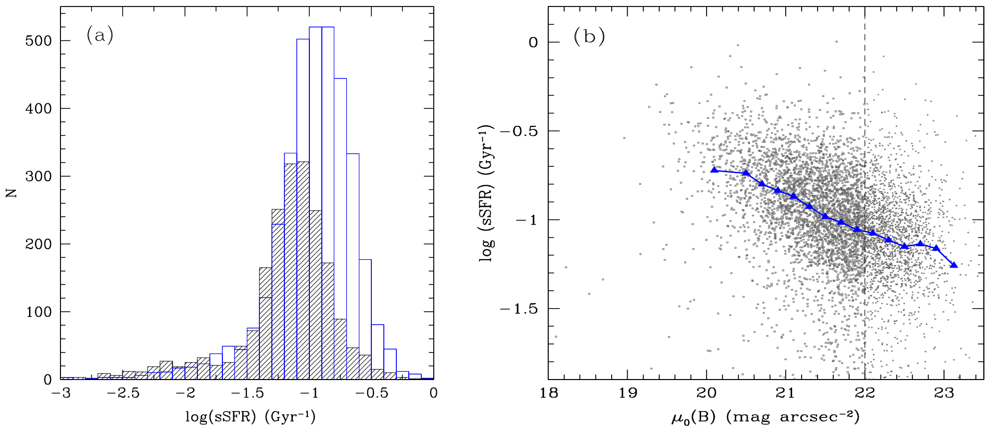

**Fig. 5** The histogram distributions of specific SFRs (a). Shadowed and unfilled regions are for LSBGs and HSBGs respectively. The relation between specific SFRs and surface brightness (b). Solid triangles, the solid line, and the dashed line are the same as in Fig. 3.

### 3.4 Specific SFRs

Given the strong correlation between SFRs and stellar masses, it is clear that by normalizing the SFRs by the stellar masses, one can more easily study the relationship between star formation activity and the physical parameters of the galaxies (Brinchmann et al. 2004). Although the distributions of stellar masses for LSBGs and HSBGs in the volume-limited samples are similar, we could further remove the effect of stellar masses by comparing the specific SFRs of LSBGs with those of HSBGs.

The specific SFRs are also from Brinchmann et al. (2004). The median value of specific SFRs for LSBGs (shadowed regions) is –1.12 Gyr$^{-1}$ (Fig. 5(a)) which is 0.18 Gyr$^{-1}$ smaller than that of HSBGs (unfilled regions). Kolmogorov-Smirnov tests show that the difference in the means of distributions for LSBGs and HSBGs is up to 34.9%. This result is consistent with the result of Section 3.3, which shows that the LSBGs have smaller SFRs than HSBGs but are nearly the same stellar masses as HSBGs. Hence LSBGs should have lower specific SFRs than those of HSBGs. Furthermore, the specific SFRs decrease rapidly with the decrease of surface brightness, i.e. the lower the surface brightnesses are, the lower specific SFRs they have (Fig. 5(b)). LSBGs with lower specific SFRs could also be related to the Kennicutt criterion for ongoing star formation, and LSBGs form stars in longer periods of time (e.g. Galaz et al. 2011). The slope of specific SFRs versus surface brightness is slightly steeper than the slope of SFRs versus surface brightness; the Spearman rank order correlation coefficient is –0.40. This may be due to the effects of stellar masses that have been further removed in calculating specific SFRs. Both Figures 4 and 5 show that the current star forming activities of HSBGs are more active than those of LSBGs.

The specific SFRs have often been rephrased in terms of the present to past-average star formation rate, which immediately gives an indication of the past star formation history of the galaxy and its relation to present-day activity, e.g. the birthrate parameter $b$ (the present-to-past average SFR ratio, Kennicutt et al. 1994; Brinchmann et al. 2004; Galaz et al. 2011). Following equation (2) in Galaz et al. (2011), we found that there is a fraction of 88.2% for LSBGs with $b$ less than 1, while the corresponding fraction of HSBGs is 66.8%. It means that the average $b$ parameter is higher in HSBGs than in LSBGs (Galaz et al. 2011), and the average value of the $b$ parameter for our LSBGs is similar to that of Galaz et al. (2011), 0.59 versus 0.65.

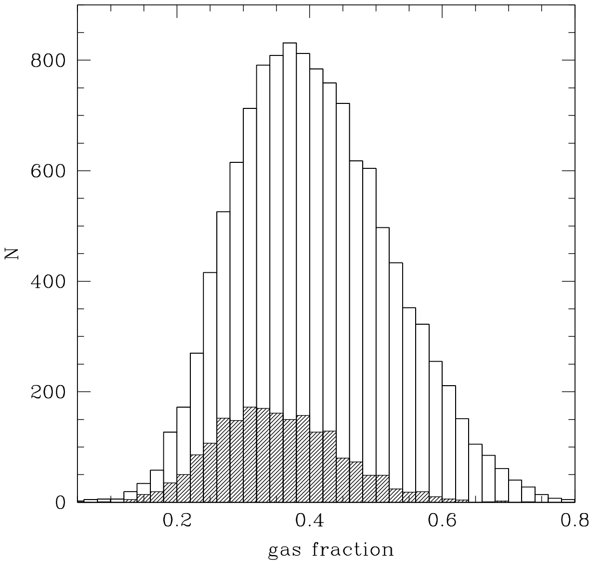

**Fig. 6** The histogram distributions of gas fraction for volume-limited LSBGs (2021, shadowed regions) and all LSBGs (12 282, unfilled regions).

## 4 DISCUSSION

The previous studies about stellar metallicities, $M_*/L$, SFRs and gas fractions of LSBGs have traditionally been carried out with very small samples. With the advent of the large sky survey of SDSS, it is now possible to dramatically extend these studies in size, and it may also improve the quality of measurements because their large amount of high-quality data will undoubtedly be important in allowing the study of properties of those galaxies more carefully.

Moreover nearly all the previous studies of stellar metallicities, $M_*/L$, SFRs and gas fractions for LSBGs are based on magnitude-limited samples, which could be affected by selection effects. We try to avoid the selection effects on the studies of LSBGs by using volume-limited samples in this work. We greatly extend the number of LSBGs, which help to study the statistical properties of LSBGs. Fortunately, our volume-limited samples of LSBGs and HSBGs have very similar stellar masses that can help acquire a fairer comparison between their other properties because it nearly removes the effect of stellar masses.

However, could the different properties between LSBGs and HSBGs studied above be caused by the fact that the volume-limited sample contains a larger fraction of gas-poor galaxies? We can calculate the gas fraction for all the parent LSBGs (i.e. 12 282 LSBGs) and HSBGs (i.e. 18 051 HSBGs) using the same formula of Zhang et al. (2009). In Figure 6, as an example, we show the histogram distributions of gas fraction for volume-limited LSBGs (2021, shadowed region) and all parent LSBGs (12 282, unfilled region). The median value of gas fraction for all parent LSBGs is 39.8%, which is only 5.2% higher than that of volume-limited LSBGs (34.6%). The median value of gas fraction for all HSBGs is 29.0%, which is only 3.1% higher than that of volume-limited HSBGs (25.9%). Therefore, although we could lose some gas-rich LSBGs and HSBGs when selecting volume-limited samples, this would not affect our results too much because we just lose a very small fraction of gas-rich galaxies, and the fraction we lose for LSBGs and HSBGs is very similar.

Furthermore, we compare the gas fraction in our volume-limited LSBGs with that of a small sample of LSBGs in McGaugh & de Blok (1997) to see whether or not our volume-limited LSBGs have a significantly different gas fraction from previous studies. For example, the gas fraction in McGaugh & de Blok (1997) for LSBGs is from 17% to 77%, which is very similar to the range of our volume-limited LSBGs (15% to 70%). The median value of gas fraction for the LSBGs in McGaugh & de Blok (1997) is 40.1%, which is not very different from our volume-limited LSBGs (34.6%), only 5.5% higher than ours. This means that our volume-limited LSBGs could be a reasonable sample to represent the properties of LSBGs.

## 5 SUMMARIES

In this paper, we continue our studies on the properties of a large sample of LSBGs from SDSS. We select a relatively large complete volume-limited sample of LSBGs from SDSS DR4 following Zhong et al. (2008) to study their properties and compare their properties with HSBGs. This large sample of LSBGs is useful for studying the statistical properties of LSBGs. By using the volume-limited samples of LSBGs and HSBGs, we can avoid the bias introduced from the differences in the distributions of the redshift and absolute magnitude for our samples. Moreover our volume-limited LSBGs have similar stellar masses to HSBGs that further remove the effect of stellar mass. The results can be summarized as follows:

1. LSBGs tend to have lower effective dust attenuations in the $z$ band with a median value of 0.34 mag, which is 0.11 mag lower than that of HSBGs. This means that LSBGs contain less dust than HSBGs.
2. The distributions of stellar masses are nearly the same for the two samples, both of which have a median value of 2.19 $\times 10^{10}$ $M_\odot$. However, the median value of stellar metallicities, $\log(Z/Z_\odot)$, for LSBGs is still 0.11 dex lower than that of HSBGs. In addition, LSBGs have higher mass-to-light ratios (in the $z$ band, Kauffmann et al. 2003). The median value of mass-to-light ratios in the $z$ band ($M_*/L_z$) after extinction correction is 1.11, which is 0.15 higher than that of HSBGs.
3. LSBGs are likely to have a higher gas fraction than that of HSBGs, with a median value of gas fraction 8.7% higher. There is a tight correlation between gas fraction and surface brightness where galaxies with lower surface brightness have higher gas fraction, and the slope of gas fraction versus surface brightness for LSBGs is slightly steeper than that of HSBGs. Although we may lose some gas-rich LSBGs when selecting our volume-limited LSBGs, we find that the gas-fraction of our volume-limited LSBGs is not much different from all the parent LSBGs (34.6% versus 39.8%). Moreover, our large sample of LSBGs has a similar gas fraction as that of McGaugh & de Blok (1997) who used a small sample of LSBGs.
4. LSBGs have lower SFRs with a median value of 1.77 $M_\odot$ yr$^{-1}$, which is 0.86 $M_\odot$ yr$^{-1}$ lower than that of HSBGs, which suggests that HSBGs underwent more recent star forming activities than LSBGs. However the median value of SFRs for LSBGs in our work is not as low as in previous studies. Moreover, the SFRs decrease with decreasing surface brightness, i.e. the higher the surface brightness is, the stronger present star forming activities they have.
5. The specific SFRs of LSBGs are also lower than those of HSBGs, and the specific SFRs also decrease with decreasing surface brightness, but the slope of the relation between specific SFRs and surface brightness is slightly steeper than that of SFRs and surface brightness, which may be due to the effects of stellar masses that are further removed in calculating specific SFRs.

In summary, LSBGs have different star formation histories from HSBGs and HSBGs may have stronger star forming activities than LSBGs.

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